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Interactions Between Multiple Seam Longwall and Room-and-Pillar Operations–A Case Study in Boone County, WV

By Gregory J. Chekan and Rudy J. Matetic

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	lbf/ft^3	pound (force) per cubic foot
ft^2	square foot	pct	percent
in	inch	psi	pound (force) per square inch
lbf/ft	pound (force) per foot	psig	pound (force) per square inch, gauge

INTERACTIONS BETWEEN MULTIPLE SEAM LONGWALL AND ROOM-AND-PILLAR OPERATIONS–A CASE STUDY IN BOONE COUNTY, WV

By Gregory J. Chekan[1] and Rudy J. Matetic[1]

ABSTRACT

In order to reduce waste and improve resource conservation, mine planning, and development, the U.S. Bureau of Mines is investigating the effects of multiple seam interactions associated with longwall coal mining. Field investigations were conducted at a mine located in Boone County, WV, where a longwall panel was operating subjacent to room-and-pillar workings in an overlying seam. To assess the effects of overlying workings on longwall headgate stability, the Bureau gathered various geotechnical information at this minesite. Headgate pillars and entries were instrumented and monitored to study their behavior during side-abutment loading as the longwall panel approached and passed beneath the overlying room-and-pillar developments. The two operations are separated by 800 ft of interburden, and although interactions between operations separated by this distance are uncommon, geomechanical measurements indicate the occurrence of an interaction. These measurements show that convergence on the headgate entries was most adverse subjacent to barrier pillars in the overlying mine. Pillar measurements indicate that side-abutment pressure increases were slightly greater than predicted values. Several factors related to both geology and mine design, believed responsible for this large interactive distance, are discussed.

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INTRODUCTION

Mining one coal seam without interference from workings in other seams is becoming increasingly uncommon in the Eastern United States. Interactions between operations in different seams can be the cause of serious ground problems predominantly in the States of Kentucky, Virginia, and West Virginia where there are many minable coalbeds. Historically, room-and-pillar mining has dominated eastern U.S. coal production. Coalbeds were mined in no particular order and with little planning between mines to reduce ground control problems. Seam sequencing was based primarily on ownership, availability, and economics, with little regard to the conservation of adjacent coals. Longwall mining has increased conservation through extraction efficiency, but the stress fields induced by workings in other vertically adjacent seams can increase the risk of mining. A better understanding of the effects of old room-and-pillar workings on longwall loading and strata behavior will become increasingly important to the future of this mining system.

Multiple seam interactions involving longwall operations have been documented in various case and model studies (*1-6*).[2] There are a variety of geologic and engineering design parameters that influence interactive distance, magnitude, and location. Researchers have demonstrated the importance of geology in seam interaction (*1*). Overburden and interburden thickness, stratification, and physical characteristics all influence the interaction to some degree. Case study documentation of seam interval beyond which interactive effects are not encountered can range from 110 ft to as much as 750 ft, implying that seam interaction should not be dismissed based on a large seam interval alone (*3*). The physical composition of the interburden is also a critical factor because many innerbeds of soft strata, such as shales, transfer load more readily as compared with harder, monolithic strata, such as sandstone, which tend to dampen interactions (*1*).

The interaction mechanism, whether it be pillar load transfer or subsidence, is fixed by the geologic environment. Therefore, to control interactions between workings, modification of the engineering design parameters is required. Design modifications for reducing interaction effects have been sought through both empirical and theoretical research. Barrier edges and gob-solid boundaries in seams either above or below are common producers of high stress, as field and model studies have shown that these features can affect the loading behavior of both the longwall panel and gate entries (*1-6*). In the case of pillar load transfer, where an upper seam is developed first, research indicates that the angle at which the longwall panel intersects barrier edges and gob-solid boundaries can affect both interaction magnitude and location (*5*). In general, the magnitude of the interaction on the longwall face is most severe when mining approaches the boundary at a 90° angle, but problems are more localized and usually occur directly subjacent to the boundary or edge. As the angle of approach increases or decreases, the magnitude of the interaction is less severe, but ground instabilities may affect a larger area on the longwall face and gate entries. In case of subsidence, where a lower seam is extracted first using room-and-pillar methods, research shows that ground problems on the longwall face and gate entries are difficult to control regardless of panel orientation or angle of approach (*5*). Successful ground control within the multiple seam environment requires accurately locating high-stress zones and adjusting mine plans accordingly, but no single standard design can satisfy the variety of conditions encountered in the field. Essentially, each operation may represent a different set of geologic conditions; therefore, varied design techniques will be required to contend with each seam interaction.

Longwall mining is economically attractive because of its efficiency and production potential. As the number of longwall operations increase, the likelihood of encountering old room-and-pillar workings will also increase accordingly. As part of its program to conserve our national resources, the U.S. Bureau of Mines conducted this research to gain insight into the effects of multiple seam workings on longwall operations. Ultimately, this knowledge will lead to improvements in longwall planning, design, and production.

MINE LOCATION, BACKGROUND, AND GEOLOGY

The study mine is located in Boone County, WV, as shown in figure 1, and is operating in the Eagle Coalbed. Directly superjacent 800 ft, the Dorothy Coalbed has been worked using room-and-pillar mining. The mine had previously experienced ground problems in the gate entries when longwall panels under overlying room-and-pillar developments were extracted. Ground problems usually were not encountered during longwall panel extraction, but

[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

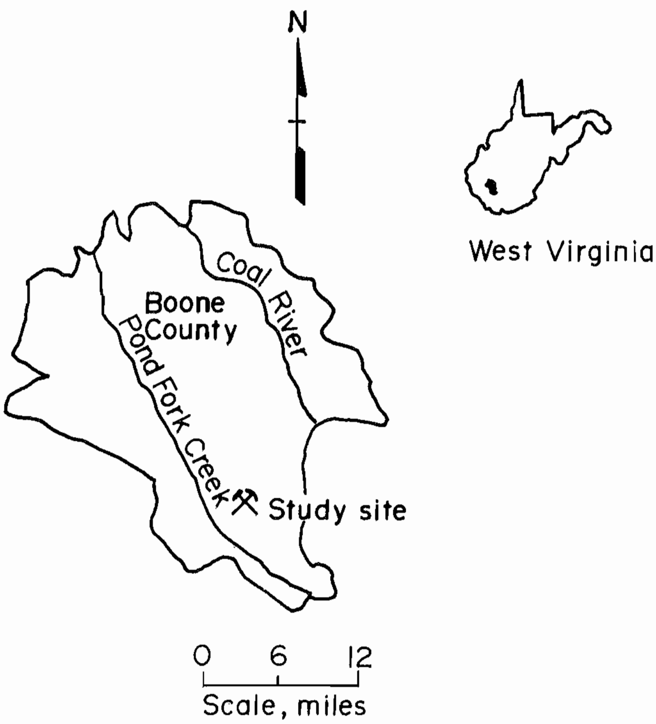

Figure 1.–Location of study mine.

rather after side-abutment loading when the longwall face had advanced well beyond these areas. Visual observation of differences in ground behavior showed that gate entries located subjacent to overlying workings tended to produce more entry convergence and pillar instability as compared with gate entries where overlying workings were not encountered. With this information, the Bureau attempted to detect these interaction effects through the use of geomechanical instrumentation.

A generalized stratigraphic column representative of the study area is shown in figure 2. The overburden above the Dorothy Coalbed ranges from 500 ft to outcrop and predominantly consists of sandstone with some interbedded shales. The interburden between the Eagle and Dorothy Coalbeds consists of near equal percentages of shale and sandstone. The interburden is 46 pct shale, 47 pct sandstone, and 7 pct coal.

The average height of the Eagle Coalbed in the study headgate is 72 in. Ten 20-ft-deep, NX-sized coreholes were drilled in the study area to further identify the stratigraphy and physical properties of the roof and floor rock. Figure 3 shows the types encountered during the coring procedure. The cores showed that the immediate roof is composed of 6 to 8 ft of a dark gray to black shale overlain by a light gray, fine- to medium-grained sandstone. The floor is composed of 2 to 3 ft of a dark gray shale underlain by a competent unit consisting of gray shale with interbedded sandstone ranging from 12 to 14 ft thick. A light gray, medium-grained sandstone composes the last 2 to 3 ft of the floor column. The cores also indicated that these strata varied slightly in thickness, but no abrupt changes in strata type were encountered. Physical property testing of the rock types showed that the sandstone and shale in the roof and floor were similar in both physical description and properties. The physical properties of the three rock types–sandstone, shale, and shale with interbedded sandstone–are given in table 1.

Table 2 presents additional site-specific information concerning mining in the Eagle and Dorothy Coalbeds.

Table 1.–Physical properties of three rock types composing roof and floor of study area

	Sandstone	Shale	Shale-interbedded sandstone
Strength, psi:			
Uniaxial compressive	15,100	10,250	16,000
Indirect (disk) tensile	1,010	950	1,325
Elastic modulus .. 10^6 psi	5.3	3.9	4.2
Poisson's ratio	0.26	0.25	0.31
Density .... lbf/ft^3	162.2	168.3	166.2

Table 2.–Site-specific coalbed information

	Dorothy	Eagle
Mining status	Inactive	Active
Mining method	RP	LW
Av mining height ...... in	80	70
Av entry width .... ft	20	20
Av pillar dimension ..... ft	40 by 60	70 by 80
Panel width .... ft	NAp	680
Panel length .... ft	NAp	5,400
In situ coal strength (σ_i) . psi	NA	[1]900

LW Longwall.
NA Not available.
NAp Not applicable.
RP Room and pillar.
[1]From reference 8.

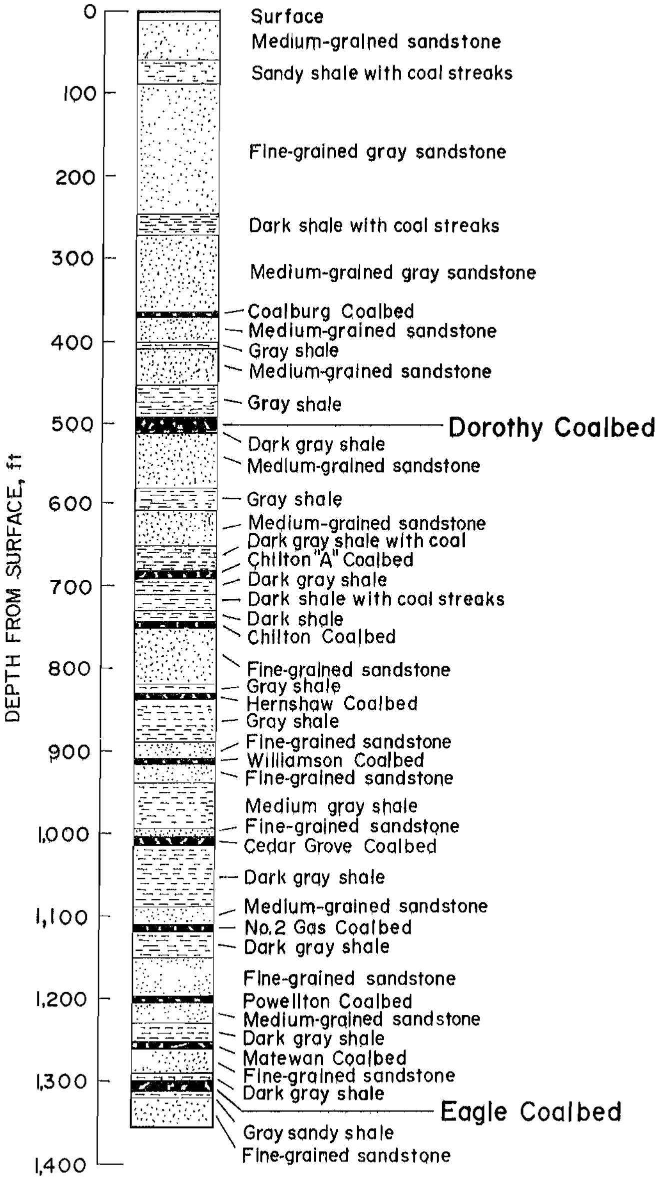

Figure 2.–Generalized stratigraphic column of study area.

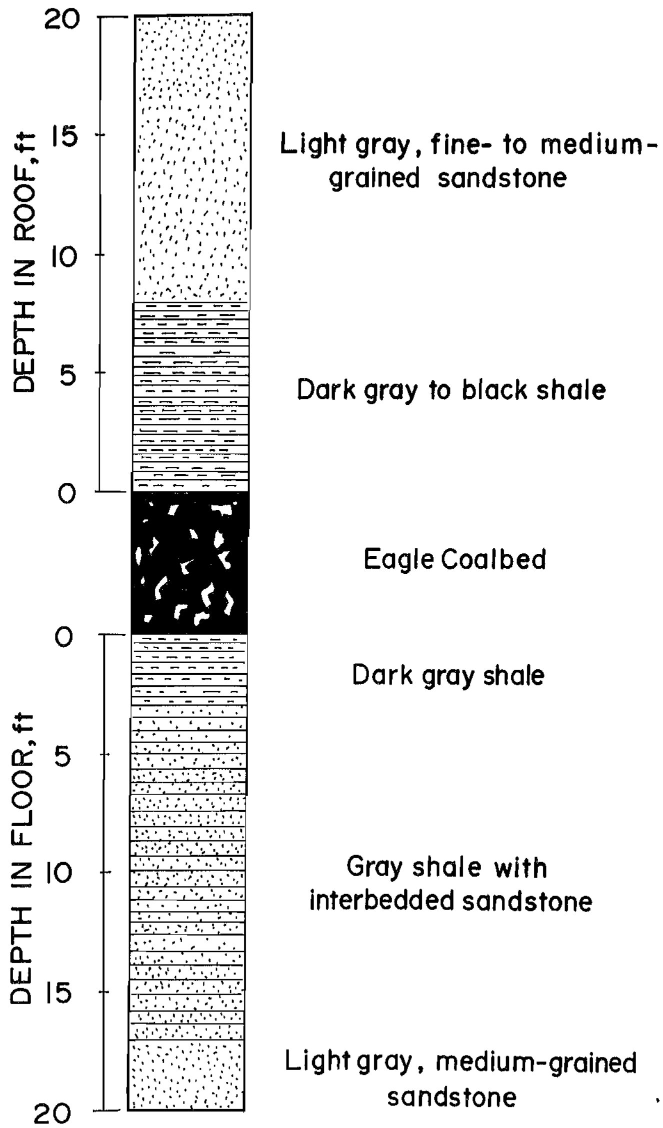

Figure 3.–Stratigraphy of roof and floor rock of study area.

LOCATION OF INSTRUMENTATION

The area of the headgate selected for study is shown in figure 4. Overburden in this area above the Dorothy Coalbed ranges from 300 ft to outcrop. Instruments were installed in a portion of the headgate where room-and-pillar panels in the upper mine intersect the longwall panel at approximately a 135° angle with respect to the headgate entry and the direction of longwall panel mining. Figure 5 shows an enlargement of the study area. Instrumented pillars P1 and P2 were located under room-and-pillar developments, and instrumented pillars P3 and P4 were located under the outcrop barrier pillar in the upper mine. It was anticipated that the stress fields associated

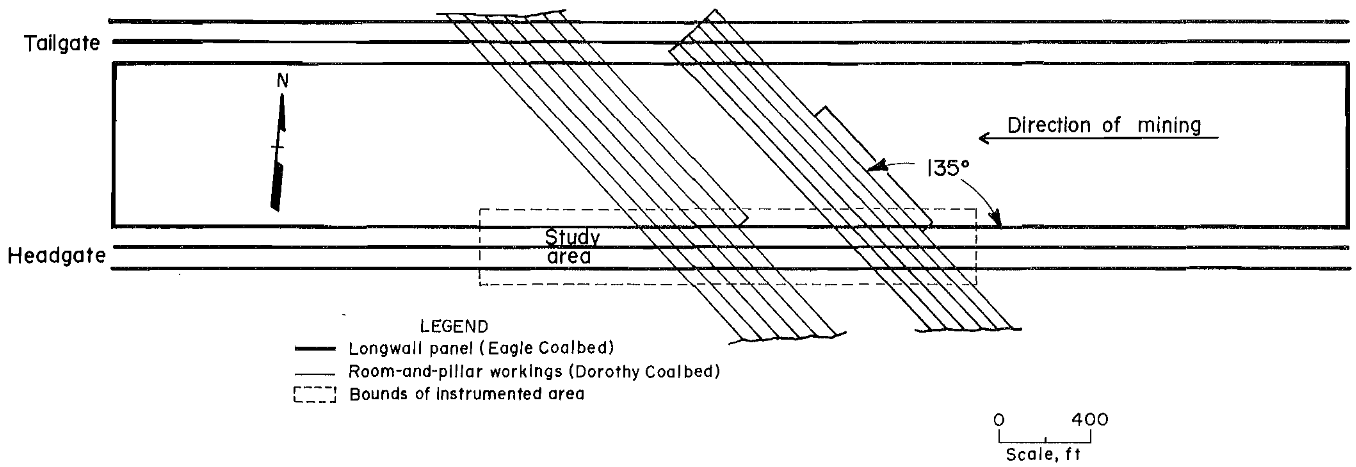

Figure 4.–Study area along headgate entry.

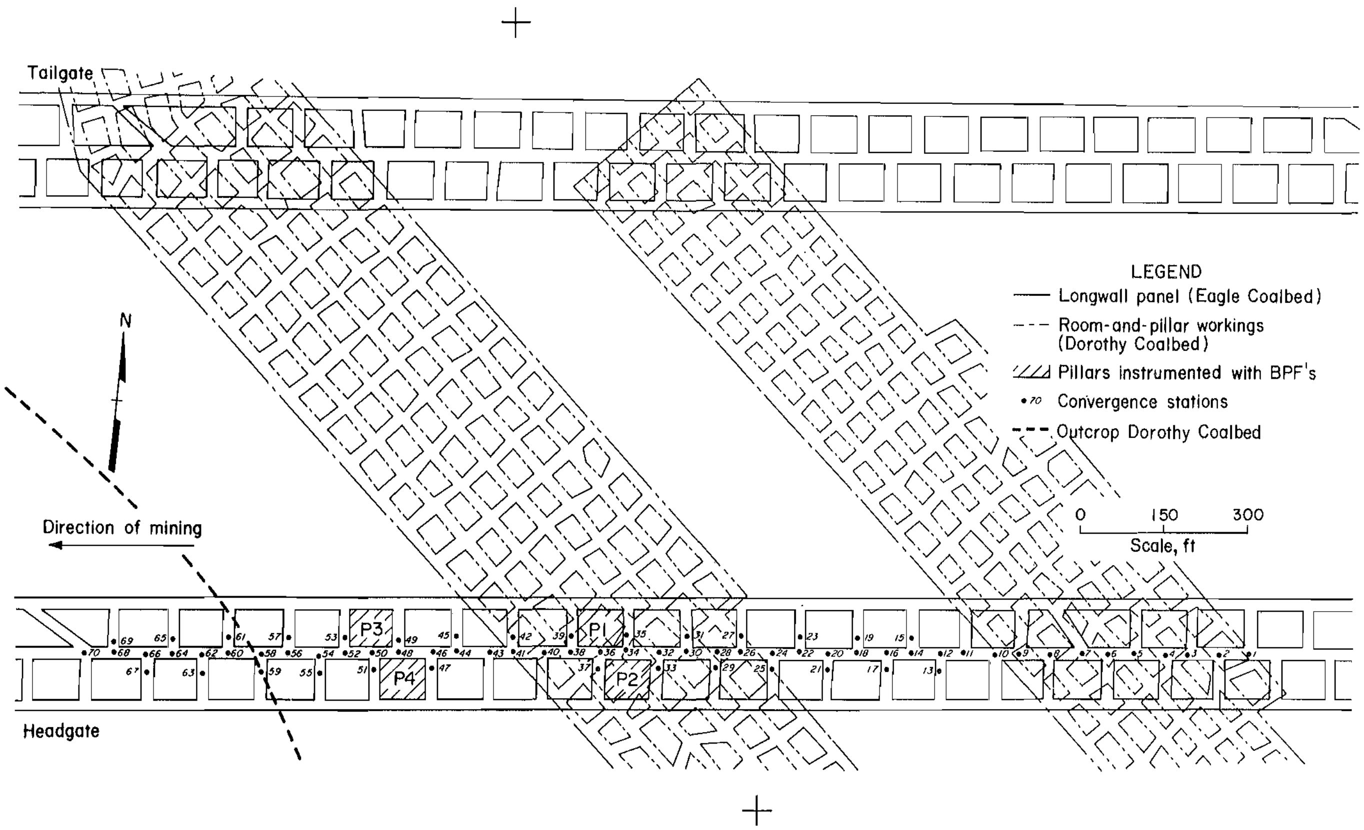

Figure 5.–Enlargement of study area showing location of instrumented pillars and convergence stations.

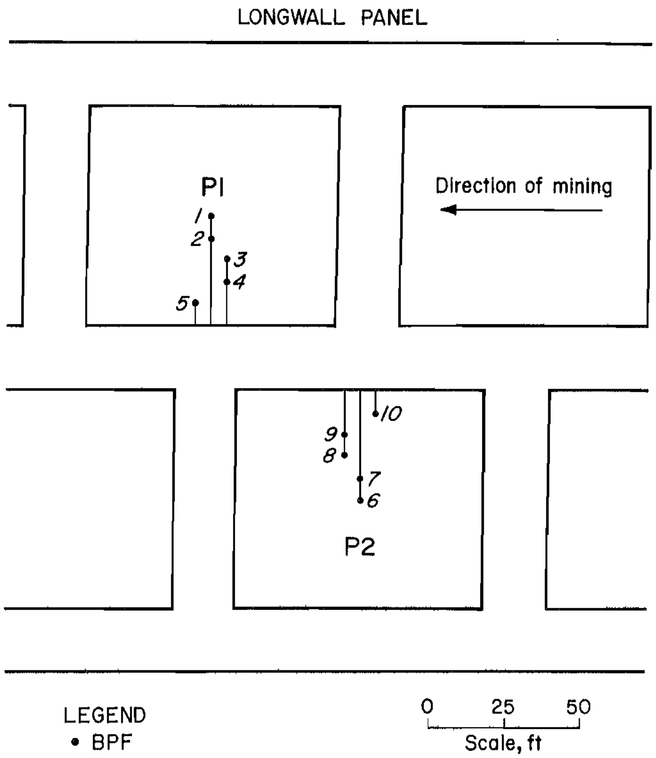

Figure 6.–BPF installation depths for pillars P1 and P2.

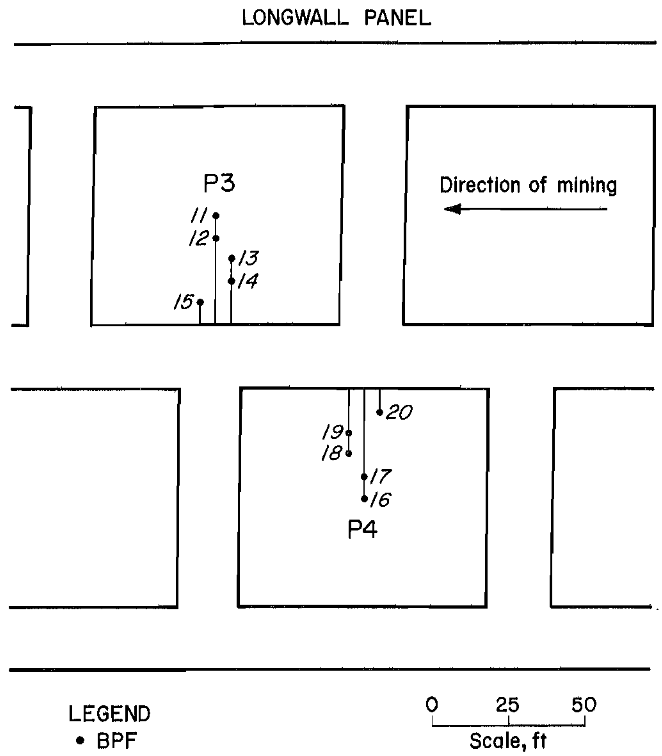

Figure 7.–BPF installation depths for pillars P3 and P4.

with mining in the upper seam would affect the longwall side abutment and increase the average load on headgate pillars.

Two types of instruments were used in the study area–convergence stations and borehole platened flatjacks (BPF's) (7). Convergence stations were used to measure entry convergence and consist of two reference pins, one in the roof and one in the floor, between which measurements are made with a tube extensometer. Seventy stations were installed in the headgate. Their locations are shown in figure 5.

The BPF is used to measure increases or decreases in pillar pressure (7). The BPF is a simple and inexpensive instrument consisting of a copper flatjack positioned between two aluminum platens. The device is installed in a 2-in-diameter borehole in the pillar, and the flatjack is inflated with hydraulic oil to a predetermined setting pressure. The BPF can be oriented in the borehole to measure pressure change in any direction. A total of 20 BPF's were installed in the 4 selected pillars of the headgate. Figures 6 and 7 show the installation depths of the BPF's in pillars P1 through P4. Five BPF's were installed across the half width of each pillar at depths ranging from 7 to 35 ft in 7-ft spacings. All BPF's were oriented to measure vertical changes in pillar pressure.

RESULTS FROM CONVERGENCE MEASUREMENTS

To assess the effects of overlying workings on headgate entry stability, convergence stations were utilized. As figure 5 shows, 70 convergence stations were installed in intersections and crosscuts of the headgate entry. Figure 8 shows convergence with relation to longwall face position for selected stations 3, 12, 26, and 50. Convergence at most stations resembled these profiles, where convergence was typically negligible until the longwall reached a face position of approximately 300 ft approaching a particular station. At this face position,

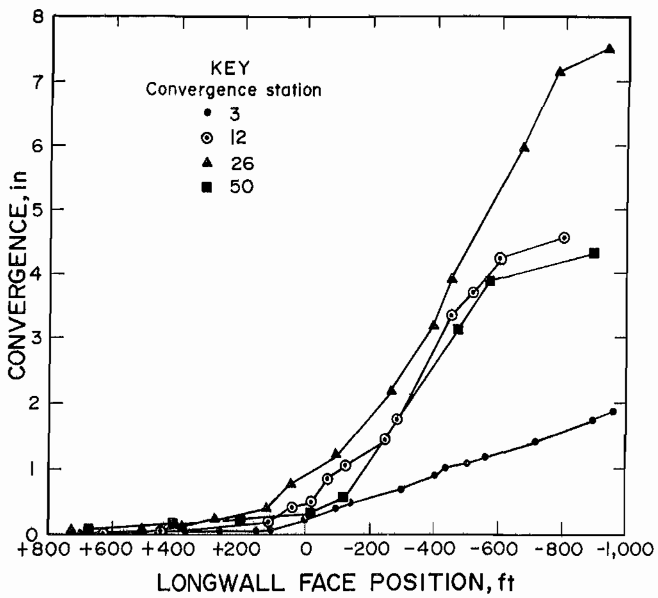

Figure 8.-Convergence versus longwall face position for stations 3, 12, 26, and 50.

convergence rates increased until the face was over 600 ft past a station. Although observation indicated that convergence was continuing, over 50 pct of the stations could no longer be monitored past 600 ft because of poor ground conditions. Both excessive floor heave and fractured roof were observed in many entries. A comparative assessment of entry convergence required a method of standardizing each station with relation to longwall extraction. As a result, a longwall face position of 300 ft approaching to 600 ft past a station was selected as the standard.

Figure 9 shows three profile lines (A, B, and C) along the 2,150-ft length of headgate where convergence stations were installed. Profile A includes the line of stations in crosscuts closest to the longwall panel; profile B includes stations in the T-intersects of the middle entry, and profile C includes stations in the crosscuts furthest from the panel. Figure 10 shows these three profiles as graphs of total convergence that was measured at each station between longwall face positions of 300 ft approaching to 600 ft past each station. Also shown is the position of workings in the Dorothy Coalbed in relation to the 2,150-ft instrumented section of the headgate and the identification of five zones. Zone 1 includes the first room-and-pillar development; zone 2 is the barrier pillar that separates the two panel developments; zone 3 includes

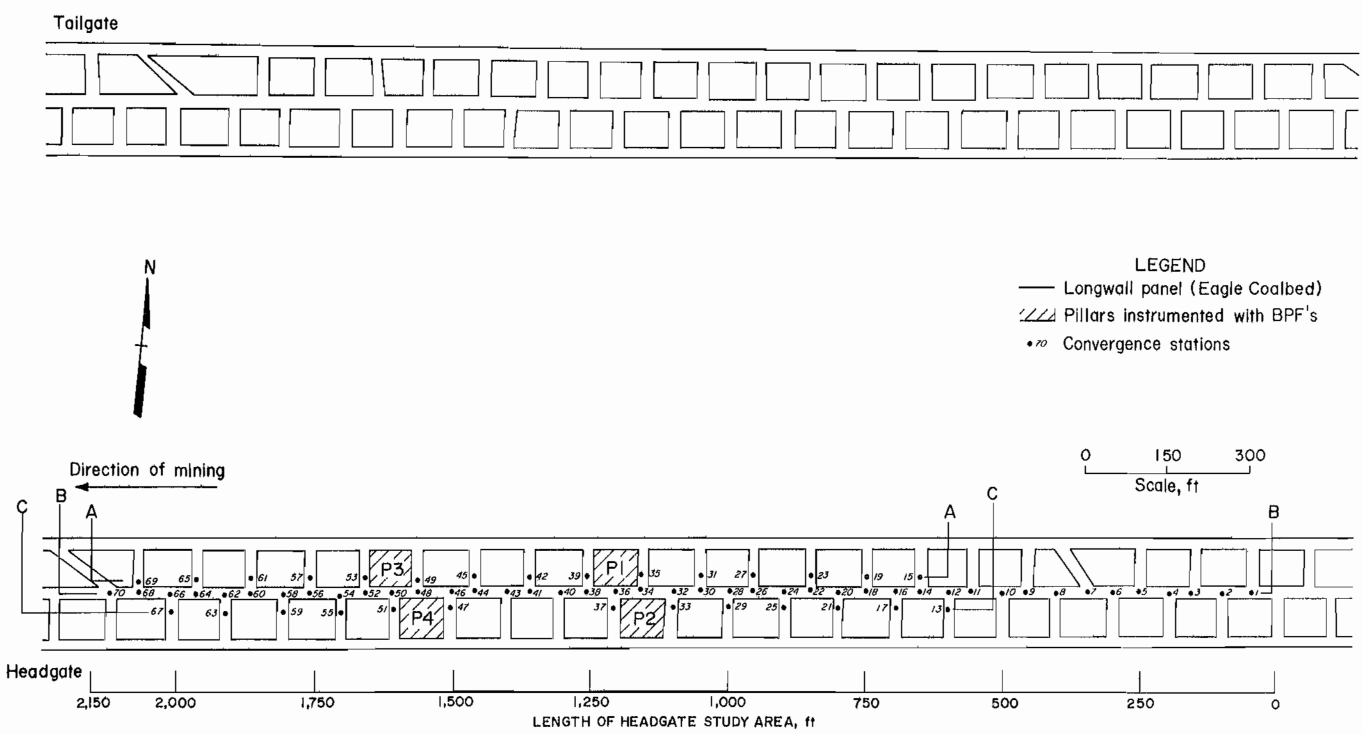

Figure 9.-Profile lines A, B, and C for convergence stations along 2,150-ft headgate study area.

the second room-and-pillar development; zone 4 includes the outcrop barrier pillar, and zone 5 represents an area not influenced by the Dorothy Coalbed.

Figure 10 also shows the convergence profile graphs for each zone in relation to mining in the upper seam. In zone 1, when longwall mining first encountered the room-and-pillar developments, convergence gradually increased, as shown in profile B. The average convergence for these 10 stations was 2.98 in. In zone 2, all three profiles (A, B, and C) show that convergence increased substantially in entries subjacent to the barrier pillar, averaging 6.15 in for these 15 stations. In zone 3, headgate entries were again subjacent to room-and-pillar developments. Profiles A, B, and C are similar in trend, showing that convergence decreased at the center of the overlying workings, but gradually increased at the solid coal edge. The average convergence for these 17 stations was 3.81 in, slightly larger than the average convergence value under the first room-and-pillar panel. In zone 4, headgate entries, subjacent to the outcrop barrier pillar, again showed an increase in convergence averaging 4.02 in for 17 stations. In zone 5, the headgate entries were not influenced by the Dorothy Coalbed and convergence decreased substantially, averaging 0.88 in for 11 stations.

The analysis indicates that the headgate entries respond differently, depending on their location with respect to upper seam mining. Similar convergence trends are evident because there exists a direct correlation between the amount of convergence the headgate entries experienced and their relation to the Dorothy Coalbed seam developments. The entries most adversely affected were located in zones 2 and 4, subjacent to the barrier pillars. At these entries, approximately 50 pct more convergence was recorded than at those entries located subjacent to the room-and-pillar developments in zones 1 and 3, and 470 pct more convergence than those entries located in zone 5 where the Dorothy Coalbed was no longer encountered. These data support other studies that show that barriers and abutments are common producers of ground instability in lower operations because of the large load-carrying capacity of those pillars. Underground conditions support these convergence trends because floor heaving and small localized roof falls occurred more frequently in entries located beneath the barriers as compared with other entries.

PREDICTING HEADGATE ABUTMENT LOADS

Gate entry pillars experience three separate types of loading during their lifetime. The first loading occurs during headgate development and is a result of the weight of the overburden supported by the pillar. A second headgate loading results from the front and side-abutment as the longwall approaches and passes the pillar. A third loading results in the tailgate during the extraction of a second, adjacent panel. One method for estimating the first and second headgate load is based on the tributary area method and the concept of the abutment angle (*8*). The development load per unit length of gate entry is represented by the following equation:

$$L_t = H\,[W_{pt} + (n-1)W_e]\gamma, \tag{1}$$

where L_t = development load per unit length of gate entry, lbf/ft,

H = depth of cover, ft,

W_{pt} = total width of pillars across gate entries, ft,

n = number of gate entries,

W_e = gate-entry width, ft,

and γ = average unit weight of overburden, 160 lbf/ft^3.

The side-abutment is defined as the additional load supported by the pillar after the face has passed. The load per unit length of gate entry is represented by the following equation:

$$L_s = \left(\frac{HP}{2} - \frac{P^2}{8 \tan \beta}\right) \gamma, \tag{2}$$

where L_s = side-abutment load per unit length of gate entry, lbf/ft,

H = depth of cover, ft,

P = panel width, ft,

β = abutment angle, 21°,

and γ = average unit weight of overburden, 160 lbf/ft^3.

This equation is for subcritical panels where P is smaller than twice (H tan ß).

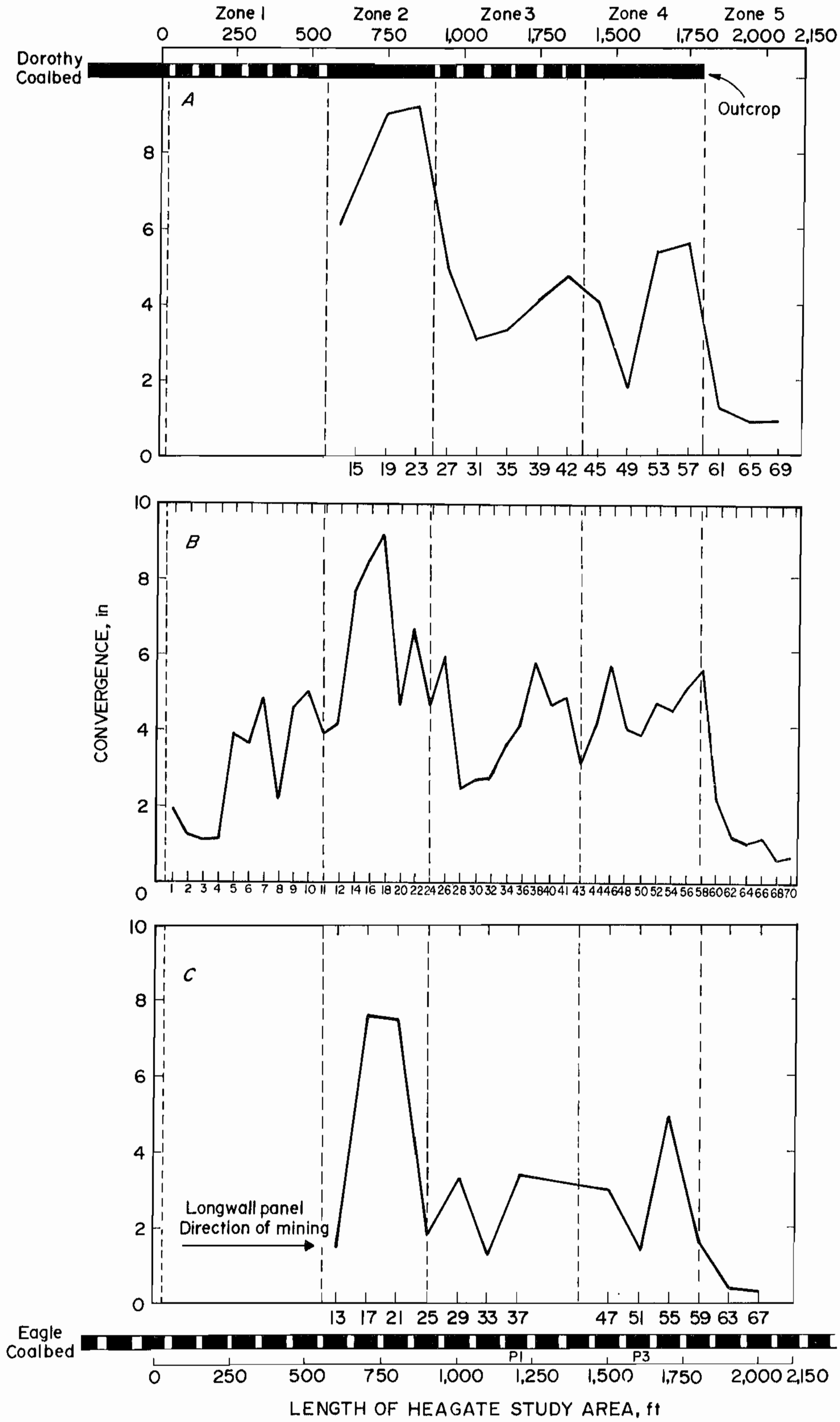

Figure 10.–Convergence in headgate entries in relation to upper seam mining. *A*, Profile A; *B*, profile B; *C*, profile C. (Numbers directly below panels designate convergence stations.)

The front-abutment is defined as the average load increase experienced by the pillar when the longwall face is parallel to that pillar. It is represented by the following equation:

$$L_f = (F)(L_s), \quad (3)$$

where L_f = front-abutment load per unit length of gate entry, lb/ft,

F = front-abutment factor, 0.51,

and L_s = side-abutment load per unit length of gate entry, lbf/ft.

To convert these linear loads (L_t, L_s, L_f) from pound per foot to a load per unit area [pound (force) per square inch], the following equation is used:

$$\sigma_t, \sigma_f, \sigma_s = (L_t, L_f, L_s)\ C/144\ A_{pt}, \quad (4)$$

where σ_t = average stress on pillar after development, psi,

σ_f = average increase in pillar stress due to front-abutment, psi,

σ_s = average increase in pillar stress due to side-abutment, psi,

L_t = overburden load, lb/ft,

L_s = side-abutment load, lb/ft,

L_f = front-abutment load, lb/ft,

C = crosscut spacing, ft,

and A_{pt} = total area of pillars, ft^2.

Table 3 lists the values for σ_s and σ_f in the instrumented area of the headgate and the values of other variables in equations 1 through 4. The σ_s and σ_f values do not take into account the development stress (σ_t) supported by the pillar and therefore represent additional loads.

Table 3.–Predicted longwall abutment loads in study area

Depth of cover (H)	ft	1,150
Panel width (P)	ft	680
Gate entries (n)		3
Total width of pillars across gate entries (W_{pt})	ft	140
Gate-entry width (W_e)	ft	20
Crosscut spacing (C)	ft	100
Total area of pillars (A_{pt})	ft^2	11,200
Load, 10^7 psi:		
Overburden (L_t)		3.31
Side abutment (L_s)		3.85
Front abutment (L_f)		1.96
Av stress on pillar after development (σ_t)	psi	2,050
Av increase in pillar stress, psi:		
From side-abutment load (σ_s)		2,380
From front-abutment load (σ_f)		1,200

RESULTS FROM PILLAR LOAD MEASUREMENTS

BPF's were installed to determine if room-and-pillar developments in the Dorothy Coalbed would affect the loading behavior of headgate pillars after side-abutment loading. As shown in figure 5, four pillars were instrumented: pillars P1 and P2 located under room-and-pillar developments and pillars P3 and P4 located under the outcrop barrier.

BPF readings were initiated when the longwall face was 500 ft away and approaching pillars P1 and P2 and continued until the face was over 1,000 ft past pillars P3 and P4. The setting pressure for all 20 BPF's was 1,000 psig. Calibration tests conducted on BPF's suggest that at this setting pressure, the change in BPF gauge pressure as it relates to changes in strata pressure is approximately a 1:1 ratio (7). Figure 11 shows the recorded pressure changes for BPF's 6 through 10 that occurred as the longwall face approached and passed pillar P2. The pressure changes shown in these graphs are similar to the pressure changes that occurred in the other three pillars (P1, P3, and P4). Typically, pressure increases were first detected when the longwall face was almost parallel to the instrumented pillar. Pressure changes continued to increase until the longwall face was 600 to 700 ft past the pillar, then gradually stabilized.

Table 4 lists the final pressure increase readings for the 20 BPF's and the average pressure increase experienced by each pillar because of the side-abutment. These increases represent pressure changes over the initial setting pressure of 1,000 psig. The largest average pressure increase of 3,920 psi was recorded at pillar P1. Average pressure increases very similar to the predicted side-abutment load of 2,380 psi (table 3) were recorded at the remaining pillars (P2 through P4). Although at pillar P1, a much higher average side-abutment load than the predicted value was recorded, it appears that the overlying workings had little effect on the side-abutment loading of headgate pillars.

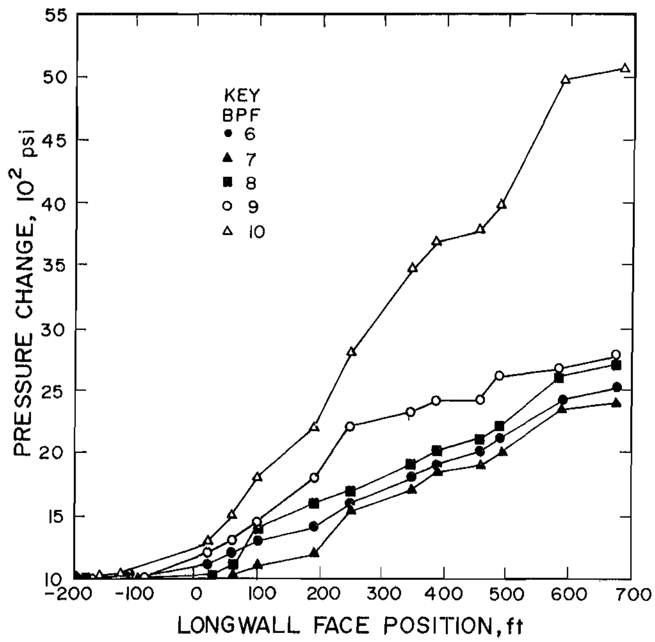

Figure 11.–BPF pressure increases versus longwall face position for pillar P2.

Table 4.–Final pressure increases for BPF's 1 through 20 (BPF setting pressure, 1,000 psig)

Pillar and BPF	Installation depth, ft	Pressure, psi Increase	Pressure, psi Av per pillar
P1:			
1	35	4,000	
2	28	4,000	
3	21	4,000	3,920
4	14	3,600	
5	7	4,000	
P2:			
6	35	2,100	
7	28	2,200	
8	21	2,400	2,460
9	14	1,600	
10	7	4,000	
P3:			
11	35	3,200	
12	28	3,200	
13	21	1,000	2,520
14	14	2,600	
15	7	2,600	
P4:			
16	35	1,100	
17	28	1,400	
18	21	2,000	2,280
19	14	3,800	
20	7	3,100	

For additional evaluation of pillar loading behavior, pressure change profiles were utilized. Figures 12 and 13 show the final pressure increases, shown in table 4, versus

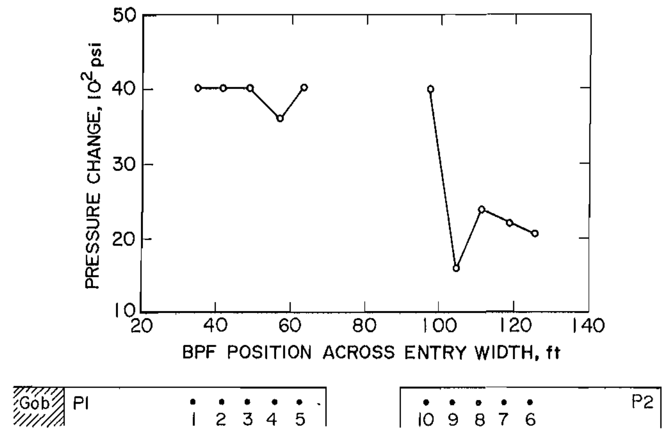

Figure 12.–Pressure change profile across headgate width due to side-abutment load for pillars P1 and P2.

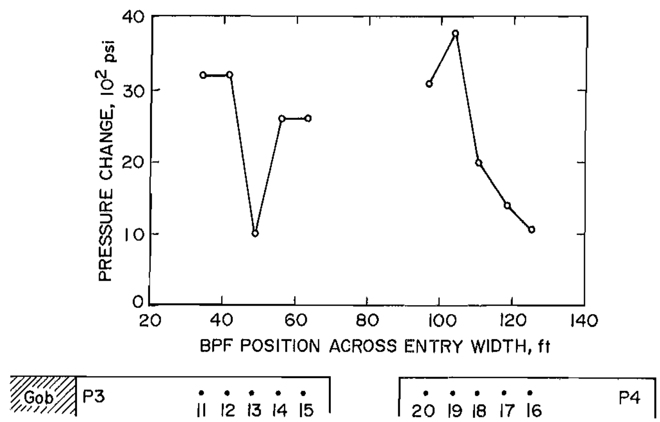

Figure 13.–Pressure change profile across headgate width due to side-abutment load for pillars P3 and P4.

the respective BPF position across the headgate width. These profiles are similar for both pillar sets in that at pillars P1 and P3, located closest to the panel, the highest pressure increases for these pillars were recorded at midpillar, an indication of pillar instability because the pillar core is carrying the majority of the load. Pillars P2 and P4, located furthest from the panel, also experienced similar loading profiles since the highest pressure increases were experienced near the pillar edge or yield zone, rather than the core, an indication of a more stable pillar.

The pillar load profiles in figures 12 and 13 are similar to profiles in previous studies (*9*) from single-seam longwall sites. These previous studies have also shown that stress across the pillar width is not always symmetric, but can be higher, specifically on the pillar side closest to the panel. Since pillars were instrumented across their half width, the side-abutment load may be slightly greater than recorded values.

ASSESSMENT OF HEADGATE PILLAR STABILITY

To evaluate the stability of instrumented pillars, safety factors were calculated using the Bieniawski-Pennsylvania State University pillar strength formula (*10*). Research shows that this formula is applicable for longwall pillars, particularly those with large width-to-height ratios (>5) (*8*, *10*). The formula is

$$\sigma_p = \sigma_i\ (0.64 + 0.36\ w/h), \tag{5}$$

where σ_p = strength of mine pillar, psi,

σ_i = in situ coal strength, 900 psi (*8*, *10*),

w = least width of pillar, 70 ft,

and h = height of pillar, 5.8 ft.

Using the variables given above, σ_p is calculated to be 4,460 psi. This pillar strength is then used in conjunction with the development load, σ_t, from table 3, to determine pillar safety factors. The safety factor after development for pillars P1 through P4 is 2.2 and is calculated by dividing σ_p by σ_t. Safety factors after side-abutment loading for pillars P1 through P4 are given in table 5 and are calculated by dividing σ_p by the estimated load on the pillar after side, abutment loading.

The recommended safety factor for pillars using this method is 1.5 after tailgate loading. Safety factors after development were well above this value for all pillars; however, a substantial reduction in safety factors resulted from the side-abutment load. For pillar P1, the upper limit of measured pillar load, the safety factor was reduced to 0.75 after side-abutment loading. For pillar P4, the lower limit of measured pillar load, the safety factor remained slightly above 1. Since pillar measurements showed that workings in the Dorothy Coalbed had little effect on the side-abutment load, an obvious conclusion is that pillars were underdesigned irrespective of the upper mine. Underground observation supports this analysis since pillars were noticeably taking weight as evidenced by rib deterioration and sloughage, particularly in pillars closest to the panel. Furthermore, as tailgate loads are applied, this will result in additional reductions in safety factors. When the Bieniawski-Pennsylvania State University formula is used, gate-entry pillars should be designed with safety factors of at least 1.5 after tailgate loads are applied. If increased loads from multiple seam interactions are suspect, this lower limit value should be increased accordingly to maintain stability.

Table 5.–Safety factors for headgate pillars P1 through P4

(σ_t, 2,050 psi; σ_p = 4,460 psi)

	P1	P2	P3	P4
Av increase in pillar pressure from side-abutment measurement . . . . psi . .	3,920	2,460	2,520	2,280
Estimated load on pillar after side abutment . . . psi . .	5,970	4,510	4,570	4,330
Safety factor after side-abutment loading	0.75	0.99	0.98	1.03

DISCUSSION

Interactions involving longwall operations separated by a large seam interval, as in this study, are rare, but have also been documented in other case studies (*3-4*). Underground measurement showed evidence of headgate interaction with overlying workings, particularly after longwall panel extraction and during side-abutment loading. This interaction could be attributed to several factors related to both geology and mine design.

In regard to geology, a highly stratified interburden may have contributed to an increase in interactive distance. Studies that relate geology to seam interaction indicate that interburden layering is an important factor influencing interactive distance (*2*). Monolithic interburdens comprised of a high-modulus rock, such as sandstone, inhibit stress transfer, while interburdens comprised of many innerbedded low-modulus rocks, such as shales, are more prone to interactions. In this study, the interburden was comprised of many innerbeds, but in nearly equal percentages of both sandstone and shale.

When mine design is considered, two factors are evident. First, the room-and-pillar developments in the upper mine transversed the longwall panel at approximately a 135° angle with respect to the longwall panel's direction of mining (fig. 4). Studies conducted on multiple seam numerical models have demonstrated that the angle of approach can affect both longwall face and entry stability when overlying workings are encountered (*5*). In general, a 90° angle of approach will produce the most severe interaction, but the area of influence will be minimized as stability problems usually occur directly subjacent to the barrier or gob-solid boundary. As the angle of approach becomes more acute or obtuse, the magnitude of interaction is less severe, but can affect a larger area of the gate entries. Second, the longwall panel was of subcritical width. This condition may have influenced interactive distance. Studies conducted with multiple seam models have shown that subcritical panels produce a special subsidence case that can be analyzed using principles of arching (*2*). Arching theory assumes that the mine opening is the major structural element in the transfer of load. Load transfer is a result of the pressure arch that forms around an underground opening upon excavation (*11*). The arch is elliptical and extends both above and below the mine opening. The magnitude of abutment pressures associated with arching and the shape and height of the arch are dependent upon the depth, the opening width, and the physical nature of the strata. Both field and model studies have shown that arches can interact with openings in other seams and can create highly stressed or destressed zones in one or both operations, depending on the geometric layout of the workings (*2*, *12*).

Interactions between longwall operations and room-and-pillar developments are difficult to predict because the complex nature of the mechanism that controls the interaction is not yet fully understood. Underground research demonstrates that when interactions between workings are suspect, the installation and monitoring of geotechnical instrumentation is a feasible method for evaluating site-specific stability problems. Information such as rock strengths, entry convergence rates, and loading characteristics of pillars can be correlated with the geologic environment and determinations made concerning the extent and magnitude of interaction. From this information, proper roof spans, pillar safety factors, and support requirements can be established for maintaining stability.

CONCLUSIONS

Based on the research conducted at the study mine, the following site-specific conclusions can be made:

1. Convergence measurements show a direct relationship between the amount of convergence the headgate entries experienced and their location with respect to the Dorothy Coalbed developments. The entries recording the most convergence after side-abutment loading were located directly subjacent to barrier pillars in the Dorothy Coalbed. At these entries, 50 pct more convergence was recorded than at entries located subjacent to room-and-pillar developments and 470 pct more convergence was recorded than at those entries located in areas where the Dorothy Coalbed was no longer encountered. These convergence data support other studies that show that barrier and abutments are common producers of ground instability in lower operations because of the large load-carrying capacity of these pillars.

2. Pillar measurements showed that changes in headgate pillar pressure, after side-abutment loading, were comparable with the predicted value of 2,380 psi, indicating that overlying workings had little effect on pillar load. Only one of four instrumented pillars showed a substantial increase over this value. Pressure change profiles show that the highest pressure increase of the pillars closest to the longwall panel was recorded at midpillar, an indication of instability because the pillar core is supporting the majority of the load. Profiles for pillars located furthest from the panel indicate that these pillars were more stable since the highest pressure increases were experienced at the pillar edge or yield zone.

3. Assessment of headgate pillar stability using the Bieniawski-Pennsylvania State University pillar-strength formula suggests that pillars were slightly underdesigned irrespective of the overlying workings in the Dorothy Coalbed. The recommended value for pillar safety factors using this formula is 1.5 after tailgate loading. The safety factors for headgate pillars ranged from 0.75 to 1.03, after side-abutment loading. These pillars would have experienced further reductions in safety factors when tailgate loads were applied. Underground observation of pillar stability supports this analysis as evidenced by rib deterioration and sloughage particularly in pillars closest to the longwall panel. When multiple seam interactions are suspect, gate road pillars should be designed with safety factors of 1.5 or greater after tailgate loading.

4. A highly stratified interburden, which consisted of many alternating beds of sandstone and shale, may have contributed to interactive distance. Studies have shown a relationship between interactive distance and the number of innerbeds that comprise the interburden (*2*).

5. The longwall panel was of subcritical width, a condition that may have also contributed to increasing interactive distance. Subcritical panels produce a special case of subsidence where arching of the strata may occur. Arches can interact with developments in other seams, creating highly stressed or destressed zones in either operation.

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